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(71) Applicants *(for all designated States except US)*: UNIVERSITY OF SOUTHAMPTON [GB/GB]; Highfield, Southampton, Hampshire SO17 1BJ (GB). BRUNEL UNIVERSITY [GB/GB]; Uxbridge, Middlesex UB8 3PH (GB).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: SAMSON, Bryce, Neilson [GB/GB]; 45 Coxford Close, Coxford, Southampton (GB). TAYLOR, Elizabeth, Regala [PH/GB]; 117 Harrison Road, Swaythling, Southampton, Hampshire SO17 3TL (GB). PAYNE, David, Neil [GB/GB]; 13 Sylvan Lane, Hamble, Hampshire SO3 5QG (GB). NAFTALY, Mira [IL/GB]; 22 Wensleydale Mews, Leeds LS12 2HT (GB). JHA, Animesh [GB/GB]; 22 Hillside Court, Gladhow Lane, Leeds LS7 4NJ (GB).

(74) Agent: TURNER, James, Arthur; D. Young & Co., 21 New Fetter Lane, London EC4A 1DA (GB).

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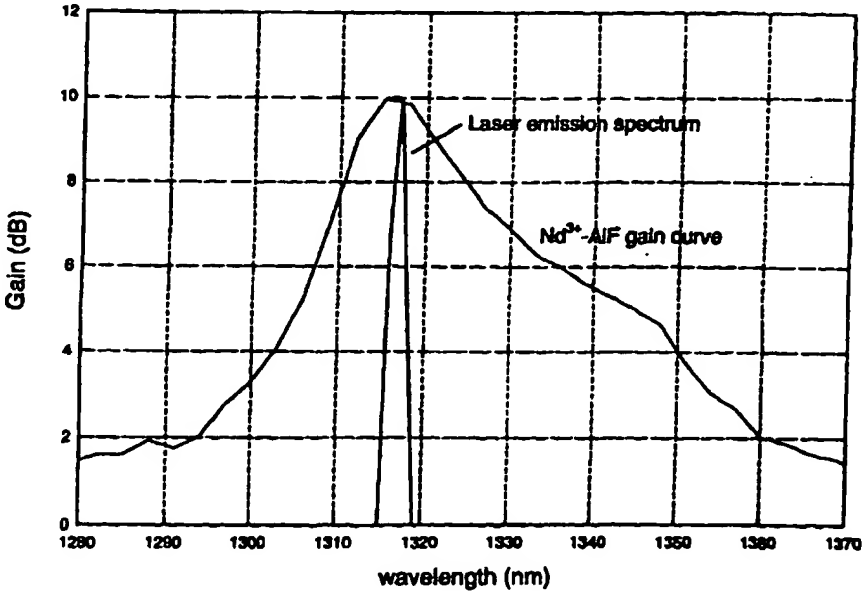

(57) Abstract

Neodymium-doped fluoroaluminate optical glass has a composition: 35 to 45 mol% AlF_3; 5 to 30 mol% RF_2, where R is selected from the group consisting of Ca, Mg, Sr and Ba; 5 to 25 mol% MF, where M is selected from the group consisting of Na, Li, K and Rb; and 0.001 to 10 mol% NdF_3 dopant.

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OPTICAL GLASS, OPTICAL WAVEGUIDE AMPLIFIER AND OPTICAL WAVEGUIDE LASER

This invention relates to optical glasses, optical waveguide amplifiers and optical waveguide lasers.

The possibility of using the $^4F_{3/2}$-$^4I_{13/2}$ transition in neodymium doped waveguides as an efficient 1.3μm optical amplifier has been the subject of many studies[1]. However there are two major drawbacks which have hindered its development.

Firstly the presence of signal excited state absorption ("ESA", see Figure 1) severely compromises the efficiency and operating wavelength of the device.

Secondly, the larger emission cross section for the 1050nm transition leads to the generation of amplified spontaneous emission (ASE) at this wavelength, which in turn clamps the available gain around 1.3μm to a relatively low value (about 5-6dB). Both these phenomena are known in the literature[1,2,3].

The ESA process is very dependent on the glass composition and a number of glass families have been studied in this regard (namely the silicates, fluorozirconates, fluoroberyllates and fluorophosphates)[1,2]. This study concluded that fluoroberyllate glasses were the optimum glass family for 1.3μm amplifiers because of their very low ESA cross section at this wavelength. However, the toxicity of beryllium rules out this glass family for practical devices. The next best family was concluded to be the fluorophosphate glasses.

It is also known that the use of discrete or continuous 1050nm ASE filters along the amplifier length allows for a significant increase in the gain at 1.3μm. Some specific ASE filtering techniques for increasing the 1.3μm gain in Nd^{3+}-doped fibre amplifiers can be found in the literature. These include the use of wavelength division multiplexers (WDMs)[6], mechanical gratings[7], the use of rare earth co-dopants to absorb the 1050nm ASE[8] and optimisation of the fibre design[9].

This invention provides an optical waveguide device formed at least in part of neodymium-doped fluoroaluminate optical glass having a refractive index, at a wavelength of 600nm, of less than or equal to about 1.444.

This invention also provides an optical waveguide amplifier operable at a peak

signal wavelength of less than 1320nm, the amplifier being formed at least in part of neodymium-doped fluoroaluminate optical glass.

This invention provides optical glass having a composition:

35 to 45 mol% AlF_3;

5 to 30 mol% RF_2, where R is selected from the group consisting of Ca, Mg, Sr and Ba;

5 to 25 mol% MF, where M is selected from the group consisting of Na, Li, K and Rb; and

0.001 to 10 mol% NdF_3 dopant.

The invention covers a range of fluoroaluminate glass compositions and, in various embodiments, their use as a Nd^{3+}-doped optical waveguide amplifier or laser operating around 1.3μm. Specifically it has been found that at least some of these compositions exhibit negligible ESA at the peak emission wavelength (1317nm) allowing efficient amplification and lasing to occur at this wavelength.

The family of glass compositions of at least embodiments of the invention have the lowest values of Nd^{3+}-1.3μm ESA cross sections of any glass (with the exception of the fluoroberyllates which are dismissed on the grounds of their toxicity) and as such are considered the optimum glass host for an efficient optical fibre amplifier operating at wavelengths around 1317nm. This is a shorter peak operating wavelength than that found in either fluorozirconate or fluorophosphate glasses both of which have lasing wavelengths longer than 1320nm[4,5]. Indeed only fluoroaluminate glasses operate efficiently at wavelengths less than 1320nm.

Thus, neodymium doped fluoroaluminate glass waveguides can be used as amplifiers and lasers within the second telecom window between 1300 and 1350nm. Specifically fluoroaluminate glasses are preferred with compositions (mol%); (35-45)AlF_3, (5-30)RF_2, (5-25 mol%)MF where R=Mg, Sr, Ba, Ca and M=Na, K, Li, Rb.

Light alkali monovalent fluorides (MF) are an advantageously important component in fluoroaluminate glass compositions intended to obtain a shorter wavelength emission and gain at the 1300nm transition of Nd^{3+}. The inclusion of significant proportions of light MF components, such as LiF and NaF gives rise to a more ionic glass with a lower refractive index. The nephelauxetic effect associated

with the low refractive index causes the emission to be blue-shifted to shorter wavelengths. High ionicity reduces the linestrength of 1300nm ESA and shifts its peak wavelength away from the centre of the emission curve. Together, the blue-shifted emission and the reduced effects of ESA result in gain at shorter wavelengths, below 1320nm.

This glass system shows a minimum excited state absorption at wavelengths around 1.3μm when doped with Nd^{3+}-ions. As a consequence these glass compositions are the only fluoride glass system (with the exception of the toxic fluoroberyllates) to operate efficiently as a waveguide amplifier or laser at wavelengths below 1320nm.

The peak gain wavelength in these glasses is 1317nm which corresponds to the peak emission wavelength thus indicating that negligible ESA occurs at this wavelength.

In order to achieve a high gain 1.3μm amplifier or laser with these glasses some degree of 1050nm ASE filtering is required. The filter response should ideally be that of a band blocking filter centred at 1050nm with around 15nm bandwidth (full width half maximum).

The neodymium-doped fluoroaluminate fibre amplifier can also offer reduced splicing loss to standard silica fibre, because the glass has a lower refractive index than silica. The refractive index is lower than in ZBLAN and fluorophosphate glasses.. As a consequence the amplifier gain is expected to be higher than in other 1.3μm neodymium-doped fibre amplifiers.

Embodiments of the invention can also provide two new techniques for 1050nm ASE filtering in Nd^{3+}-doped 1.3μm waveguide amplifiers. The first involves the use of UV induced in-core gratings, which may be written directly into the waveguide core by UV light. This process is made possible by the addition of a photosensitizing agent (eg 1mol% CeF_3 or tin fluoride) to the basic fluoroaluminate core glass composition.

The form of the grating may be either a blazed reflection grating or a long period grating coupling to discrete cladding modes. In either case the grating preferably acts as a band blocking filter, centred at 1050nm and with a bandwidth of around 15nm full width half maximum.

The complete amplifier may include many discrete filters or one continuous filter along the total amplifier length. For example, in-core gratings may be written directly into the waveguide core with UV light from, for example, an excimer laser. In order to photosensitise the glass to UV light the core glass is modified from the above compositions to incorporate small amounts (.01-5mol%) of cerium fluoride (CeF_3) or tin fluoride.

The presence of Sn^{3+} or Ce^{3+}-ions greatly increases the photosensitivity of the core glass allowing the formation of periodic refractive index changes or gratings. Careful control of the grating parameters (period, blaze angle and depth of modulation) allows the formation of 1050nm band-stop gratings with the correct bandwidth. A Nd^{3+}-doped waveguide amplifier incorporating one or more of these filters exhibits substantially more gain at wavelengths around 1.3um than amplifiers with no filter.

A second method for ASE filtering in other embodiments is based on splicing Yb^{3+}-doped fibres at intervals along the length of the Nd^{3+}-doped fluoroaluminate fibre. These fibres have around 30dB absorption at 1050nm and negligible loss at the Nd^{3+}- pump (800nm or 740nm) and signal (1317nm) wavelengths. The Yb^{3+}-doped fibre may be silica, fluoroaluminate or any other fluoride fibre. The advantage in using fluoroaluminate fibre comes from the matching of the fibre refractive indices.

The plural alternate fibre sections act as discrete 1050nm ASE filters and unlike Nd^{3+}/Yb^{3+} co-doped waveguides do not suffer from energy transfer between the two sets of ions. This greatly increases the device efficiency. (Clearly, by the use of the term "alternate", the skilled man will appreciate that the possibility of other fibres being included between the sections is not excluded).

Both these ASE filtering techniques allow high gain at around 1.3μm and do not significantly affect the slope efficiency of the device.

The short lengths possible with the Nd^{3+} are significant because both fibre and planar amplifiers and devices are then possible. Planar waveguides offer a number of features. The main advantage of waveguide devices on a chip is the potential for integration of several optical functions on a single substrate. Several aspects of device fabrication are more easily achieved in planar rather than fibre.

The invention will now be described by way of example with reference to the

accompanying drawings, throughout which like parts are referred to by like references, and in which:

Figure 1 schematically illustrates an Nd^{3+}-energy level diagram;

Figure 2 schematically illustrates the ratio of the 1.3μm emission to ESA linestrength in various glasses (AlF_3=fluoroaluminate, BeF_2=fluoroberyllate, FLP=fluorophosphate, ZrF_4=fluorozirconate);

Figure 3 schematically illustrates the gain curve for Nd^{3+}-doped fluoroaluminate glass showing the lasing spectrum for single mode fibre. The gain peak and lasing wavelength are 1317nm which corresponds to the peak emission wavelength in this glass;

Figure 4 schematically illustrates the noise figure for Nd^{3+}-doped fluorozirconate and fluoroaluminate fibre amplifiers;

Figure 5 schematically illustrates the small signal gain at 1317nm for Nd^{3+}-doped fluoroaluminate fibre amplifier and Nd^{3+}/Yb^{3+} co-doped amplifier;

Figure 6 is a schematic diagram of an Nd^{3+}/Yb^{3+} composite amplifier where the Yb^{3+} doped fibre may be silica or fluoroaluminate;

Figure 7 schematically illustrates an amplifier with discrete ASE-suppressing gratings;

Figure 8 schematically illustrates an amplifier with a continuous ASE-suppressing grating;

Figures 9 to 11 schematically illustrate planar waveguides with continuous ASE-suppressing gratings;

Figure 12 schematically illustrates a 12-way coupler incorporating an amplifier as described above;

Figure 13 schematically illustrates a laser incorporating an amplifier as described above;

Figure 14 schematically illustrates the small signal gain at 1317nm for Nd^{3+}/Yb^{3+} fluoroaluminate composite amplifier. The gain increases as the number of Yb^{3+}-doped fibre sections is increased; and

Figure 15 schematically illustrates the small signal gain for Nd^{3+}-doped fluoroaluminate fibre amplifier incorporating a 1050nm ASE suppressing gratings along the fibre length and a continuous grating along the 10cm length of the device.

Although a wide range of fluoroaluminate glasses are known and have been described in the literature their potential application in Nd^{3+}-doped 1.3μm optical waveguide amplifiers and lasers has not been considered. The fluoroaluminate glass composition can be optimised or at least improved in terms of minimising the excited state absorption cross section at around 1.3μm.

A summary of some example Nd^{3+}-doped fluoroaluminate glass compositions is shown in tables 1a and 1b, and in table 2 the ratio of the 1.3μm emission ($^4F_{3/2}$ to $^4I_{13/2}$) to 1.3μm ESA ($^4F_{3/2}$-$^4G_{7/2}$) linestrengths for each glass is given. Also included for comparison are commercial fluorophosphate glasses (LG810 and PK51A) along with a ZBLAN glass sample. A large value for the emission to ESA ratio is desirable indicating that the probability of stimulated emission is greater than absorption. Note the much improved ratio for the fluoroaluminate glasses, compared with the commercial glasses, indicating a substantial decrease in the 1.3μm ESA in these glass compositions.

Table 1a NdF_3-doped (1mol%) fluoroaluminate glass compositions

Sample	Composition	Refractive Index
59	$30AlF_3$:$10ZrF_4$:$7.5YF_3$:$3.5MgF_2$:$20CaF_2$:$11BaF_2$:$13SrF_2$:4NaF	1.441
62	$37AlF_3$:$12MgF_2$:$15CaF_2$:$9SrF_2$:$12BaF_2$:$14YF_3$	1.426
91	$39AlF_3$:$10MgF_2$:$30CaF_2$:$10SrF_2$:$10BaF_2$	1.411
108	$37AlF_3$:$12MgF_2$:$15CaF_2$:$9SrF_2$:$6BaF_2$:$14YF_3$:6NaF	1.424
115	$39AlF_3$:$9MgF_2$:$30CaF_2$:$9SrF_2$:$9BaF_2$:3LiF	1.412
116	$39AlF_3$:$8MgF_2$:$30CaF_2$:$8SrF_2$:$8BaF_2$:6LiF	1.410
117	$39AlF_3$:$7MgF_2$:$30CaF_2$:$7SrF_2$:$7BaF_2$:9LiF	1.402
121	$39AlF_3$:$6MgF_2$:$30CaF_2$:$6SrF_2$:$6BaF_2$:6LiF:6NaF	1.398
122	$39AlF_3$:$6MgF_2$:$26CaF_2$:$6SrF_2$:$6BaF_2$:8LiF:8NaF	1.401
123	$39AlF_3$:$6MgF_2$:$22CaF_2$:$6SrF_2$:$6BaF_2$:10LiF:10NaF	1.397
124	$39AlF_3$:$6MgF_2$:$18CaF_2$:$6SrF_2$:$6BaF_2$:12LiF:12NaF	1.394

Table 1b NdF_3-doped (1mol%) fluoroaluminate glass compositions

Sample	Composition	Refractive Index
129	$40AlF_3$:$6MgF_2$:$14CaF_2$:$6BaF_2$:$6SrF_2$:14NaF:14LiF	1.385
130	$40AlF_3$:$6MgF_2$:$12CaF_2$:$6SrF_2$:$6BaF_2$:15LiF:15NaF	1.383
131	$40AlF_3$:$6MgF_2$:$10CaF_2$:$6SrF_2$:$6BaF_2$:16LiF:16NaF	1.382
136	$40AlF_3$:$5MgF_2$:$22CaF_2$:$5SrF_2$:$4BaF_2$:10LiF:10NaF:$3NaPO_3$	1.383
152	$38AlF_3$:$9MgF_2$:$29CaF_2$:$9BaF_2$:15NaF	1.389

In other words, this table shows glasses having a general composition:

35 to 42 mol% AlF_3;

0 to 10 mol% MgF_2;

0 to 30 mol% CaF_2;

0 to 10 mol% SrF_2;

0 to 10 mol% BaF_2;

0 to 30 mol% LiF;

0 to 30 mol% NaF;

(having a total LiF + NaF content of 10 to 40 mol%); and

0.001 to 10 mol% NdF_3 dopant.

Table 2 Summary of Judd-Ofelt parameters for Nd^{3+}-doped fluoroaluminate glasses.

Sample	Ref. Index	λ_p (nm)	Ω_2 (x10^{-24})	Ω_4 (x10^{-24})	Ω_6 (x10^{-24})	emission/ ESA
59	1.441	1317.5	1.24	3.40	4.40	2.54
62	1.426	1317	1.37	3.15	4.47	2.66
91	1.411	1317.5	1.42	3.35	5.09	2.82
108	1.424	1317	1.08	3.33	4.32	2.67
115	1.412	1317	0.75	3.08	4.13	3.03
116	1.140	1317	0.88	3.05	4.37	3.06
117	1.402	1317	1.00	4.01	5.36	2.97
121	1.398	1317	1.38	3.97	6.05	3.04
122	1.401	1317	1.07	4.34	5.79	3.06
123	1.397	1317	1.15	3.39	5.83	3.48
124	1.394	1317	1.35	3.97	6.37	3.24
FK54	1.437	1320.5	1.79	3.50	4.41	2.15
LG810	1.453	1320	2.65	3.22	5.06	2.08
ZBLAN	1.54	1317	2.20	2.83	3.94	2.01

A summary of these results is shown in Figure 2 where we plot the ratio of the 1.3μm emission to 1.3μm ESA for a range of glass families. The best glasses, with the exception of the fluoroberyllates, are a family of fluoroaluminate glasses having a significantly reduced ESA linestrength compared to both ZBLAN and fluorophosphate glasses. The data for fluorophosphate, fluorozirconate and fluoroberyllate glasses can be found in reference 10 which includes a detail spectroscopic study of Nd-doped glasses. However reference 10 does not include

Nd^{3+}-doped fluoroaluminate glasses.

These fluoroaluminate glasses have a large proportion of AlF_3 as glass former and include in the composition large amounts of light alkali fluorides such as LiF and NaF. The light alkali fluorides combine some of the smallest ionic radii with very large electropositivities. Their presence in the glass increases the ionicity of the host and creates sites with low local basicity, leading to decreased ESA. This approach enabled us to improve the Nd^{3+} gain curve in accordance with the requirements of a 1.3 μm amplifier device. Another significant physical property of these optimised fluoroaluminate glass compositions is their very low values of refractive index (see table 1). Optimised compositions have refractive index values less than 1.43 (measured at a wavelength around 600nm) as a result of the large amounts of light alkali fluorides present in the glass.

The fluoroaluminate glass compositions may be stabilized by the addition of divalent fluorides as modifier ions. These also resulted in the creation of well-dispersed sites, thus delaying the onset of cross-relaxation to doping levels of >0.5 mol%. The lighter divalent fluorides (i.e. CaF_2 and MgF_2) were predominantly included in order to maintain the prevalent ionicity of the glass host and to preserve its low refractive index.

An enhancement of the glass stability may be obtained by adding a small amounts of phosphate (PO_3), which can improve the fibre drawing properties of the glasses. However, the inclusion of phosphate within the glass has a detrimental effect on the spectroscopic quality of the glasses. The addition of phosphate increases the ESA linestrength and shifts the emission peak wavelength to longer wavelength (see tables 3 and 4). These detrimental effects are not too severe when small amounts of phosphate (<10mol%) are used.

Table 3 NdF_3-doped (1mol%) fluoroalumino-phosphate glass compositions

Sample	Composition	Refractive Index
62	$37AlF_3$:$12MgF_2$:$15CaF_2$:$9SrF_2$:$12BaF_2$:$14YF_3$	1.426
69	$37AlF_3$:$12MgF_2$:$15CaF_2$:$9SrF_2$:$8BaF_2$:$14YF_3$:$4NaPO_3$	1.427
70	$37AlF_3$:$12MgF_2$:$15CaF_2$:$9SrF_2$:$6BaF_2$:$14YF_3$:$6NaPO_3$	1.432
71	$37AlF_3$:$12MgF_2$:$15CaF_2$:$9SrF_2$:$4BaF_2$:$14YF_3$:$8NaPO_3$	1.431
72	$37AlF_3$:$12MgF_2$:$15CaF_2$:$9SrF_2$:$14YF_3$:$12NaPO_3$	1.439
73	$37AlF_3$:$12MgF_2$:$15CaF_2$:$14YF_3$:$21NaPO_3$	1.444

In general, at least some preferred embodiments of the invention may have the composition: 35 to 45 mol% AlF_3; 5 to 30 mol% RF_2, where R is selected from the group consisting of Ca, Mg, Sr and Ba; 5 to 25 mol% MF, where M is selected from the group consisting of Na, Li, K and Rb; and 0.001 to 10 mol% NdF_3 dopant.

Table 4 Summary of Judd-Ofelt parameters for Nd^{3+}-doped fluoroalumino-phosphate glasses.

Sample	Ref. Index	τ_{meas} (μs)	τ_{rad} (μs)	λ_p (nm)	Ω_2 (x10^{-24})	Ω_4 (x10^{-24})	Ω_6 (x10^{-24})	A_{emm}/A_{esa}
62	1.426	495	556	1317	1.37	3.15	4.47	2.66
69	1.427	489	568	1317.5	1.58	3.06	4.46	2.47
70	1.432	500	602	1318	1.44	2.95	4.06	2.40
71	1.431	469	533	1319	1.73	3.49	4.54	2.25
72	1.439	488	465	1319	2.43	3.74	5.28	2.14
73	1.444	468	468	1320	2.74	3.74	5.15	1.96

Since these fluoroaluminate glasses have such low refractive index values it is difficult to fabricate high NA fibres without seriously compromising the spectroscopic parameters. For this application the addition of small amounts (e.g. up to 5 mol%) of lead, cadmium or bismuth fluoride to the core glass composition is preferred to the addition of phosphate.

The fluoroaluminate glasses were prepared from commercial high purity fluoride powders. The batch was processed throughout under the atmosphere of dry nitrogen. Prior to melting, the prepared batch was fluorinated for a period depending on the amount of impurities present, with the aim of reducing residual impurity levels. This was done using $NH_4.HF_2$ at 500°C for a period the duration of which depends on the amount of impurities (typically 2-4 hr). The glass was melted and homogenized for 4 hr at 900-950°C, depending on the composition. The glass was then cast into a mould preheated to 250-350°C, depending on the composition and the mould. The glass was annealed at near its transition temperature for a period of 12-24 hr. It was found that the quality of the glass was greatly improved by re-melting it rapidly for 20 min and re-casting it. The amount of bubbles in the glass was greatly reduced by this procedure, and homogeneity and surface quality were

considerably enhanced.

Preforms were manufactured using the following procedure. Rotational casting was used to produce cladding glass tubes with an internal diameter of 2-4mm. Core glass rods were cast in a stationary cylindrical mould and caned to match the cladding glass tube. Preforms were then produced by inserting the caned core into the cladding tube, using the rod-in-tube method. Single mode fibres were obtained by repeating the tube-in-rod process as required to achieve the desired core-to-cladding ratio.

The measured gain curve for a Nd^{3+}-doped fluoroaluminate glass fibre amplifier is shown in Figure 3. The peak of the gain curve (1317nm) also corresponds to the peak of the emission curve indicating the negligible ESA at this wavelength. Also shown in this Figure is the laser emission spectrum which for this fibre occurs at 1317nm (ie the peak of the emission curve). This was measured by butting two high reflecting mirrors (reflectivity > 80% at wavelengths between 1400nm and 1200nm and less than 10% between 1100nm and 900nm) to both of the fibre ends. Pump light at 800nm was launched through one of these mirrors. This lasing wavelength is significantly shorter than that achieved in either fluorophosphate or fluorozirconate fibres which both lase at wavelengths longer than 1320nm[4,5]. This is summarised in table 5. The laser configurations (except as described herein) are conventional.

Table 5 Comparison of Nd^{3+}-doped glass laser wavelengths

Glass	Peak Emission wavelength	Lasing Wavelength
Fluoroaluminate	1317nm	1317nm
fluorozirconate	1317nm	1330nm
Fluorophosphate	1320nm	1323nm

The shorter peak gain wavelength is desirable for applications in telecommunications where the zero dispersion wavelength is around 1310-1317nm in

most of the currently installed fibre links. Furthermore, the reduced ESA in the fluoroaluminate device gives a much lower noise figure when operated as a small signal amplifier at wavelengths less than 1340nm when compared with a ZBLAN device (Figure 4). Consequently a Nd^{3+}-doped fluoroaluminate amplifier is more desirable in telecommunications applications than a Nd^{3+}-doped ZBLAN device. Such applications are as small signal amplifiers or power amplifiers operating around 1317nm.

The small signal gain at 1317nm versus pump power for a Nd^{3+}-doped fluoroaluminate fibre amplifier is shown in Figure 5 where the gain is seen to saturate at about 6dB due to the effect of the 1050nm ASE. Also shown is the curve obtained for a Nd^{3+}/Yb^{3+} co-doped fibre amplifier. Although the gain is no longer clamped in the co-doped case the slope efficiency is much decreased with respect to the Nd^{3+}-doped device. This is due to energy transfer from the Nd^{3+} ions to the Yb^{3+} ions causing a significant decrease in the device efficiency.

In order to obtain a high gain at 1317nm without compromising the device efficiency the Yb^{3+} can be incorporated within separate sections of fibre which are then spliced into the Nd^{3+}-doped fluoroaluminate fibre (see Figure 6). The Yb^{3+}-doped fibre section need not be fluoroaluminate glass but can be silica or any other glass composition. The advantage in using fluoroaluminate fibre sections is the good match in refractive index between the Nd^{3+} and Yb^{3+}- fibre sections. Using Yb^{3+}-doped silica sections is better when angle splices are used to reduced back reflections due to the refractive index mismatch.

The Yb^{3+}-doped sections 20 inhibit ASE at 1050nm by absorbing at that wavelength. Typically, each section of Nd^{3+} doped AlF fibre might be 2cm long, and each Yb^{3+}-doped section might be 10-20m long. Fibre splices are indicated schematically by "X" symbols.

Figure 14 shows the gain at 1317nm for a fluoroaluminate fibre with the gain clamped at about 6dB. The gain curves obtained by splicing sections of Yb^{3+}-doped fluoroaluminate fibre are also shown in this Figure. The gain increases as the number of Yb^{3+}-doped fibres is increased and the device efficiency is not compromised. Clearly this is not the case for the Nd^{3+}/Yb^{3+} co-doped device.

The fluoroaluminate core glass composition can be modified to include 1mol%

CeF_3 or tin fluoride thus increasing the ultra violet (UV) absorption at about 248nm. By exposing the fibre to intense UV radiation from an excimer laser a permanent change in the glass refractive index could be formed. Refractive index changes of the order of about $1x10^{-3}$ can be produced by this means. By illuminating the fibre core with spatially modulated light from a phase mask or interferometer a periodic modulation of the fibre core refractive index can be achieved. Such a structure can act as a diffraction grating for light travelling along the fibre core. By careful control of the grating parameters (blaze angle, period and refractive index change) the grating can act as a band blocking filter for 1050nm light.

Figure 7 illustrates an alternative arrangement in which discrete ASE-suppressing gratings 25 are written or spliced into the Nd^{3+}-doped AlF fibre. For example, these could be long-period gratings which tend to divert light at 1050nm into cladding modes. Figure 8 shows a similar arrangement in which a continuous grating is written.

By writing one or more of these gratings midway along the fluoroaluminate fibre we achieve a doubling of the available gain at 1317nm due to the suppression of the 1050nm ASE (shown in Figure 15). Also shown is the gain curve for a device incorporating a 10cm long grating written the continuous length of a fluoroaluminate fibre amplifier.

UV written, grating based ASE filters may also be written in silica fibre and subsequently spliced to the Nd^{3+}-doped fluoroaluminate fibre. However this suffer the disadvantage of needing an angle splice to suppress reflections due to the refractive index mismatch.

Figures 9 to 11 illustrate similar techniques for use with planar waveguides. In particular, Figure 9 illustrates the formation of a suitable grating over an Nd^{3+}-doped light guiding core 30 by an overclad substrate. Figures 10 and 11 schematically illustrate the periodic etching of a light-guiding substrate 30.

Figure 12 schematically illustrates one potential use of these devices, in a 1x8 splitter - e.g. for the final link in a home distribution system by optical fibre. Here, an amplifier as described above having an imposed ASE-suppressing grating 40.

Figure 13 schematically illustrates a fibre laser employing an amplifier as described above with an ASE-suppressing grating 50 and two gratings 60 arranged

to reflect signal light back into the cavity between the two gratings 60 to promote lasing within the cavity.

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2. W.J. Miniscalco, in 'Rare Earth Doped Fibre Lasers and Amplifiers', Chapter 2, pp19-133, Ed. M.J.F. Digonnet (Marcel Dekker, Inc), (1993).

3. J. Obro et al, "Highly improved fibre amplifier for operation around 1300nm", Electronics Letters, 27, pp470-472, (1991).

4. EP-A-0320665.

5. E. Ishikawa, H. Aoki, T. Yamashita and Y. Asahara, 'Laser Emission and Amplification at 1.3μm in Neodymium-Doped Fluorophosphate Fibres', Electron. Lett. 28, 1492, (1992).

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8. EP-A-0462613.

9. A. Bjarklev et al "9dB Gain improvement of 1300nm optical amplifier by amplified spontaneous emission suppression fibre design", Electronics Letters, 19, pp1701-1702, (1991).

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CLAIMS

1. An optical waveguide device formed at least in part of neodymium-doped fluoroaluminate optical glass having a refractive index, at a wavelength of 600nm, of less than or equal to about 1.444.

2. A device according to claim 1, the glass having a refractive index, at a wavelength of 600nm, less than or equal to 1.389.

3. An optical waveguide amplifier operable at a peak signal wavelength of less than 1320nm, the amplifier being formed at least in part of neodymium-doped fluoroaluminate optical glass.

4. An optical waveguide laser comprising an amplifier according to claim 3.

5. A waveguide device, amplifier or laser according to any one of claims 1 to 4, the waveguide being an optical fibre.

6. A device, amplifier or laser according to any one of claims 1 to 5, in which the optical glass has a composition:

35 to 45 mol% AlF_3;

5 to 30 mol% RF_2, where R is selected from the group consisting of Ca, Mg, Sr and Ba;

5 to 25 mol% MF, where M is selected from the group consisting of Na, Li, K and Rb; and

0.001 to 10 mol% NdF_3 dopant.

7. A device, amplifier or laser according to any one of claims 1 to 5, in which the optical glass has a composition:

35 to 42 mol% AlF_3;

0 to 10 mol% MgF_2;

0 to 30 mol% CaF_2;

0 to 10 mol% SrF_2;

0 to 10 mol% BaF_2;

0 to 30 mol% LiF;

0 to 30 mol% NaF;

(having a total LiF + NaF content of 10 to 40 mol%); and

0.001 to 10 mol% NdF_3 dopant.

8. A device, amplifier or laser according to claim 6 or claim 7, the optical glass comprising between 1 mol% and 10mol% PO_3.

9. A device, amplifier or laser according to claim 6 or claim 7, the optical glass comprising one or more dopants selected from the group consisting of:

0 to 5 mol% PbF_2;

0 to 5 mol% CdF_2; and

0 to 5 mol% BiF_3.

10. A device, amplifier or laser according to any one of claims 6 to 9, the optical glass comprising one or more further dopants selected from the group consisting of cerium fluoride and tin fluoride.

11. Optical glass having a composition:

35 to 45 mol% AlF_3;

5 to 30 mol% RF_2, where R is selected from the group consisting of Ca, Mg, Sr and Ba;

5 to 25 mol% MF, where M is selected from the group consisting of Na, Li, K and Rb; and

0.001 to 10 mol% NdF_3 dopant.

12. Optical glass having a composition:

35 to 42 mol% AlF_3;

0 to 10 mol% MgF_2;

0 to 30 mol% CaF_2;

0 to 10 mol% SrF_2;

0 to 10 mol% BaF_2;

0 to 30 mol% LiF;

0 to 30 mol% NaF;

(having a total LiF + NaF content of 10 to 40 mol%); and

0.001 to 10 mol% NdF_3 dopant.

13. Glass according to claim 11 or claim 12, comprising between 1 mol% and 10mol% PO_3.

14. Glass according to claim 11 or claim 12, comprising one or more dopants selected from the group consisting of:

0 to 5 mol% PbF_2;

0 to 5 mol% CdF_2; and

0 to 5 mol% BiF_3.

15. Glass according to any one of claims 11 to 14, comprising one or more further dopants selected from the group consisting of cerium fluoride and tin fluoride.

16. An optical waveguide formed at least in part from glass according to any one of claims 11 to 15.

17. An optical fibre waveguide in which a light-guiding core is formed of glass according to any one of claims 11 to 15.

18. A waveguide according to claim 17, in which a cladding is formed of glass according to any one of claims 11 to 15.

19. An optical fibre waveguide in which the fibre cladding is formed of glass according to any one of claims 11 to 15.

20. A waveguide according to any one of claims 17 to 19, in which the core or

cladding glass has a refractive index, at a wavelength of 600nm, of less than or equal to about 1.444.

21. An optical amplifier comprising plural alternate lengths of:

(i) Yb^{3+}-doped optical waveguide; and

(ii) optical waveguide according to any one of claims 17 to 20.

22. An amplifier according to claim 21, in which the Yb^{3+}-doped waveguide is formed of a fluoride glass.

23. An amplifier according to claim 22, in which the refractive indices of the core glass of the Yb^{3+}-doped waveguide and the core glass of the optical waveguide are substantially identical.

24. An amplifier according to claim 21, in which the Yb^{3+}-doped waveguide is formed of a silica glass.

25. An amplifier according to claim 24, in which the waveguide and the Yb^{3+}-doped waveguide are lengths of optical fibre spliced at a splicing angle which is not perpendicular to the longitudinal fibre axis.

26. An optical amplifier comprising:

one or more lengths of waveguide according to any one of claims 17 to 20; and

one or more amplified spontaneous emission (ASE) suppressing optical gratings disposed at respective positions along the amplifier's length, each grating providing increased attenuation at a wavelength of about 1050nm.

27. An amplifier according to claim 26, in which each grating is a blazed reflection grating.

28. An amplifier according to claim 26, in which each grating is a long period

grating in which light at a wavelength of 1050nm is induced to couple from a light-guiding core mode to one or more modes propagating substantially outside of the light-guiding core.

29. An optical amplifier comprising:

a waveguide according to any one of claims 17 to 20; and

a distributed amplified spontaneous emission (ASE) suppressing optical gratings imposed on the waveguide, the grating providing increased attenuation at a wavelength of about 1050nm.

30. A laser comprising:

an optical amplifier according to any one of claims 21 to 29; and

reflector means to promote lasing within the optical amplifier.

31. Use of one or more dopants selected from the group consisting of up to 5 mol% PbF_2, up to 5 mol% CdF_2 and up to 5 mol% BiF_3 to raise the refractive index of a glass according to any one of claims 11 to 13.

32. Use of one or more dopants selected from the group consisting of cerium fluoride and tin fluoride to increase the photosensitivity of a glass according to any one of claims 11 to 13.

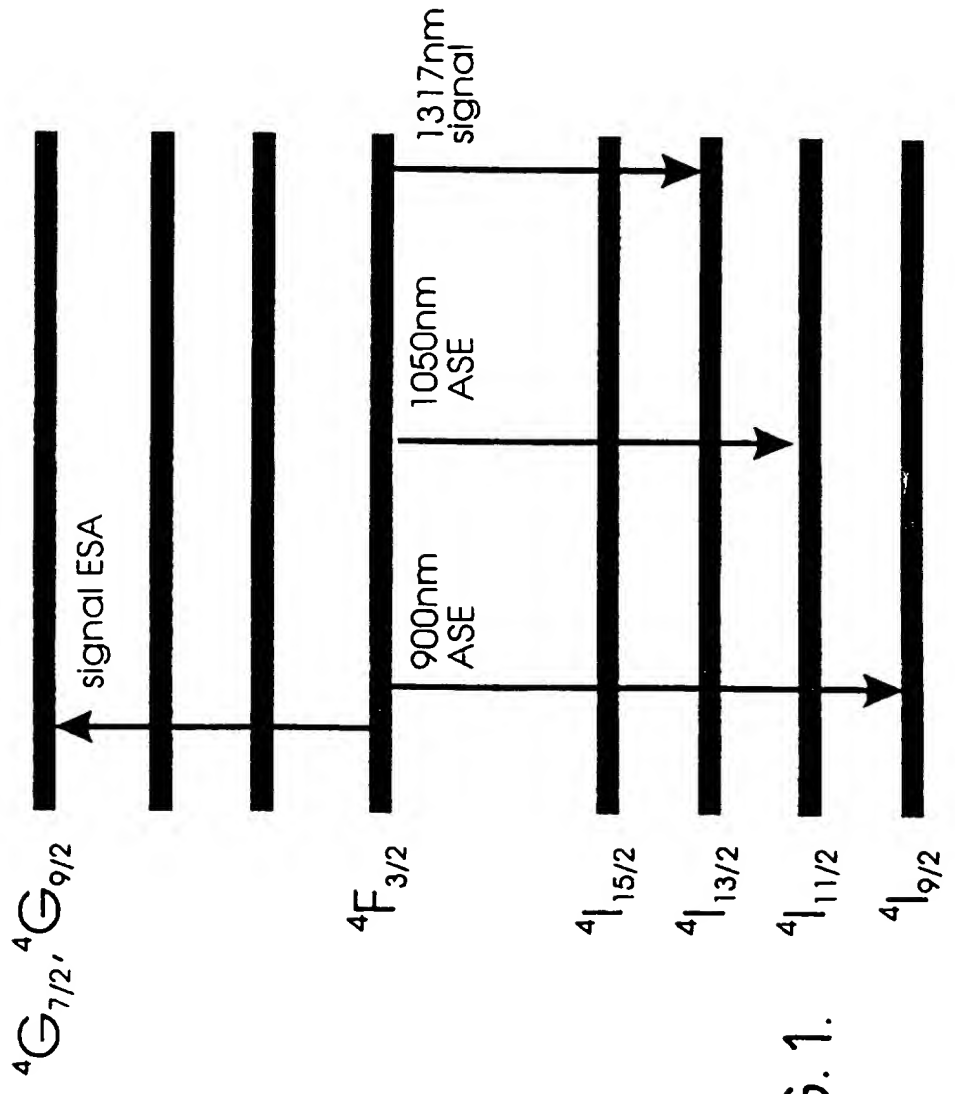

1317nm signal
1050nm ASE
900nm ASE
signal ESA
$^4G_{7/2}, ^4G_{9/2}$
$^4F_{3/2}$
$^4I_{15/2}$
$^4I_{13/2}$
$^4I_{11/2}$
$^4I_{9/2}$

FIG. 1.

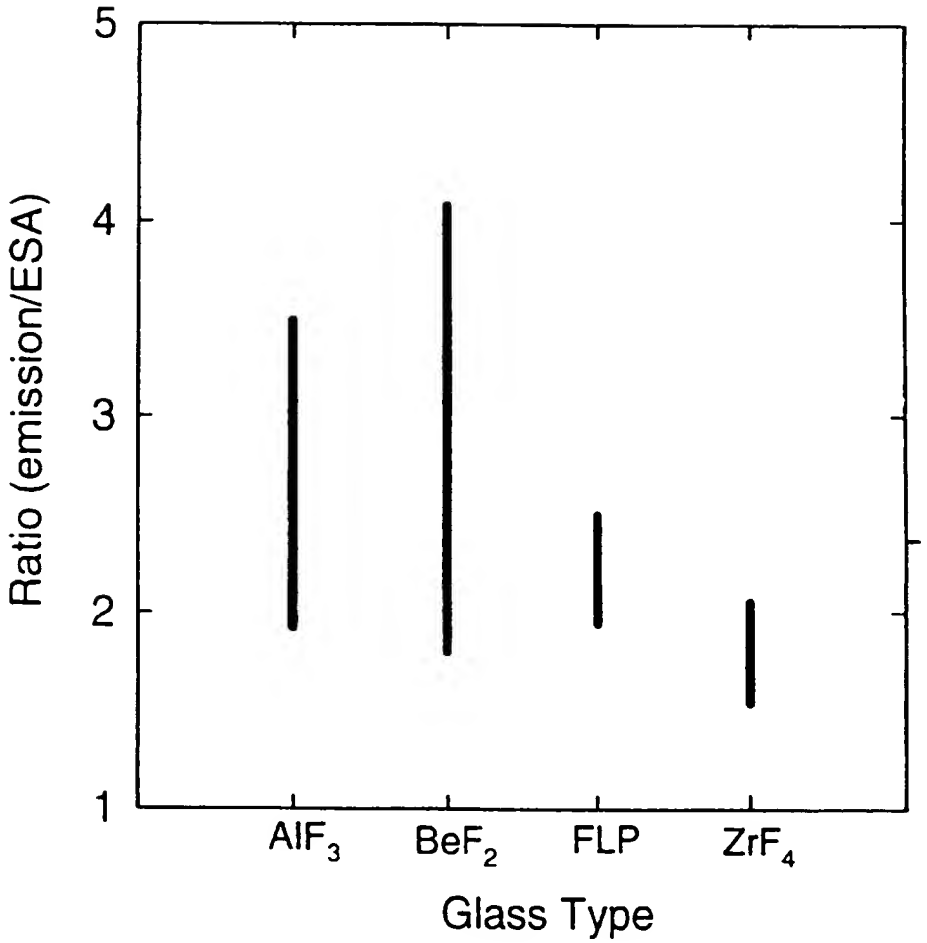


FIG. 2.

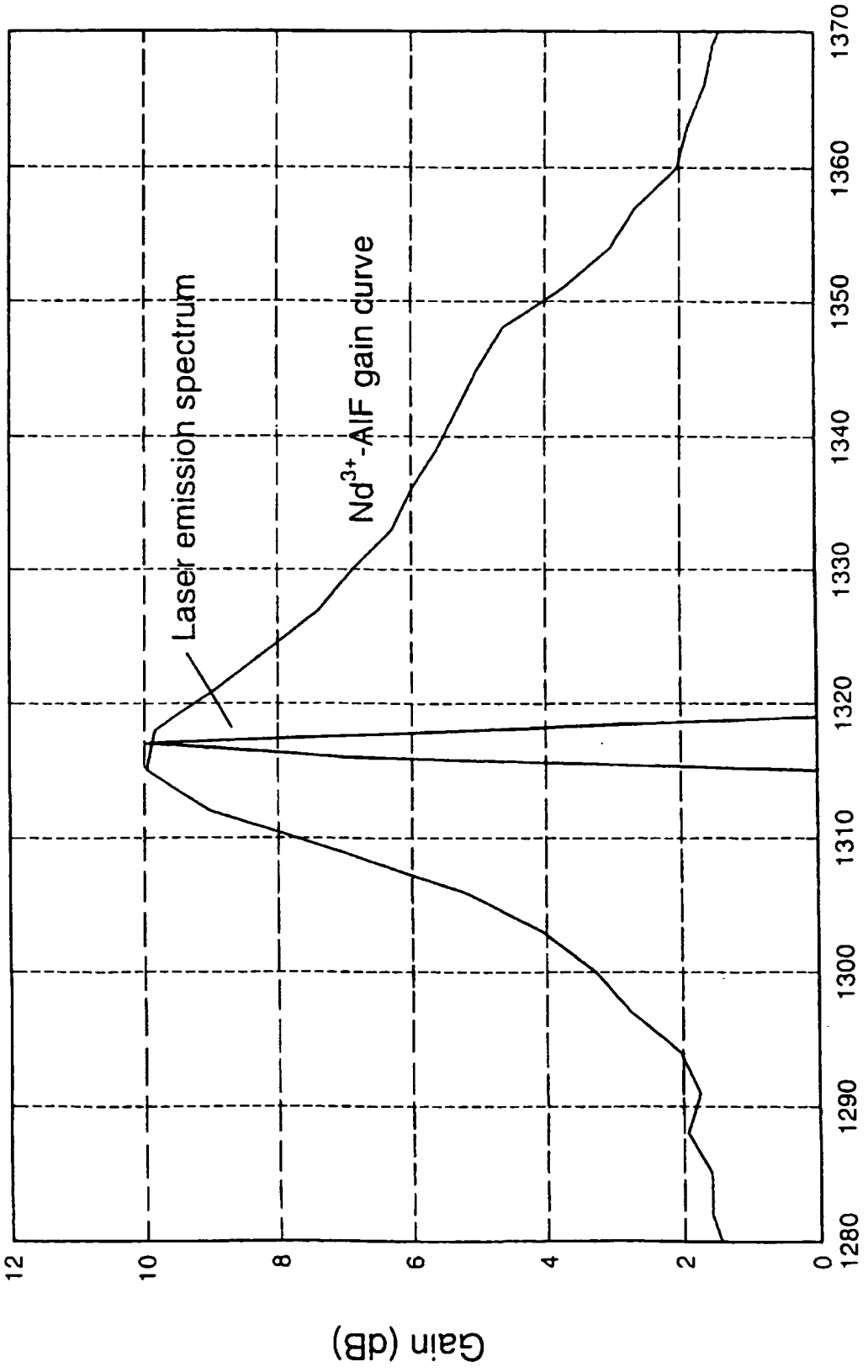

Laser emission spectrum
Nd^{3+}-AlF gain curve
Gain (dB)
0
2
4
6
8
10
12
1280
1290
1300
1310
1320
1330
1340
1350
1360
1370
wavelength (nm)

FIG. 3.

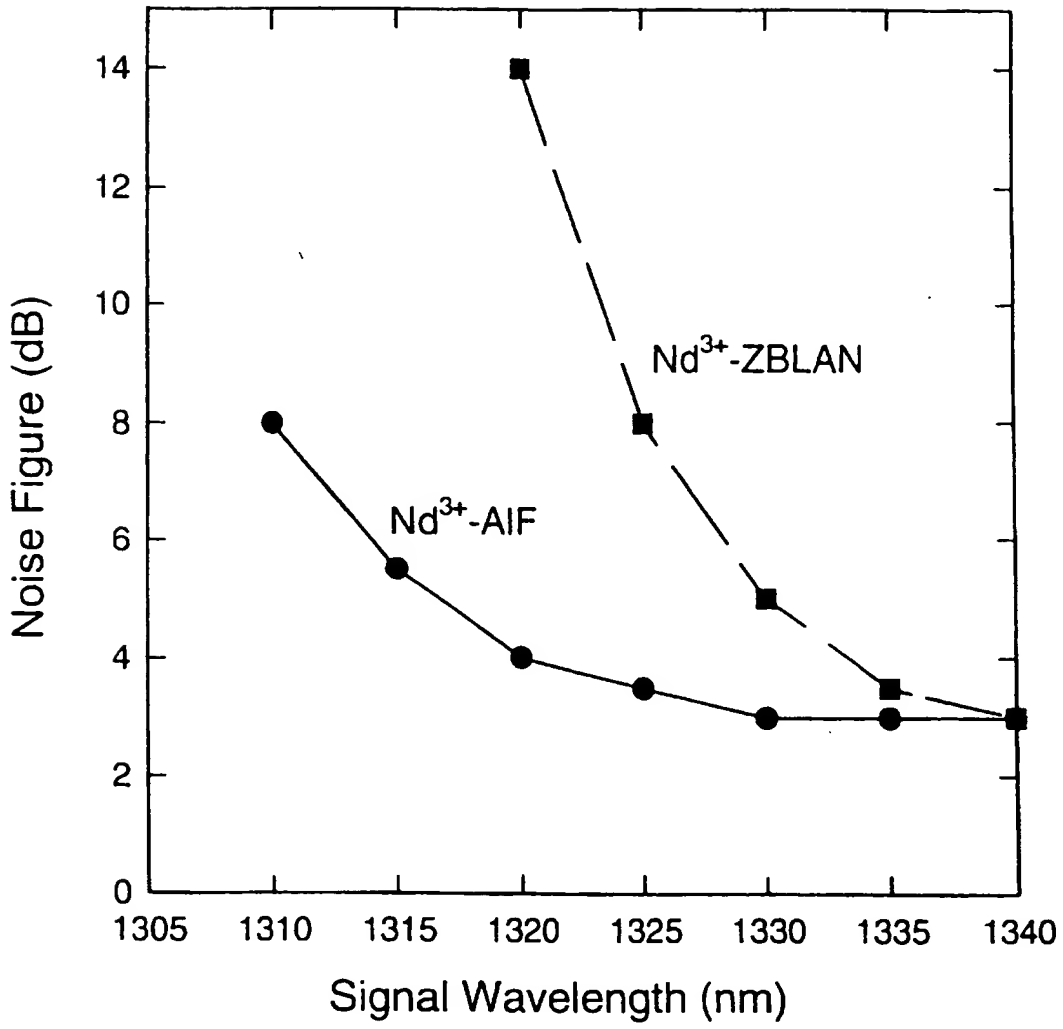

Noise Figure (dB)
0
2
4
6
8
10
12
14
1305
1310
1315
1320
1325
1330
1335
1340
Signal Wavelength (nm)
Nd3+-ZBLAN
Nd3+-AlF

FIG. 4.

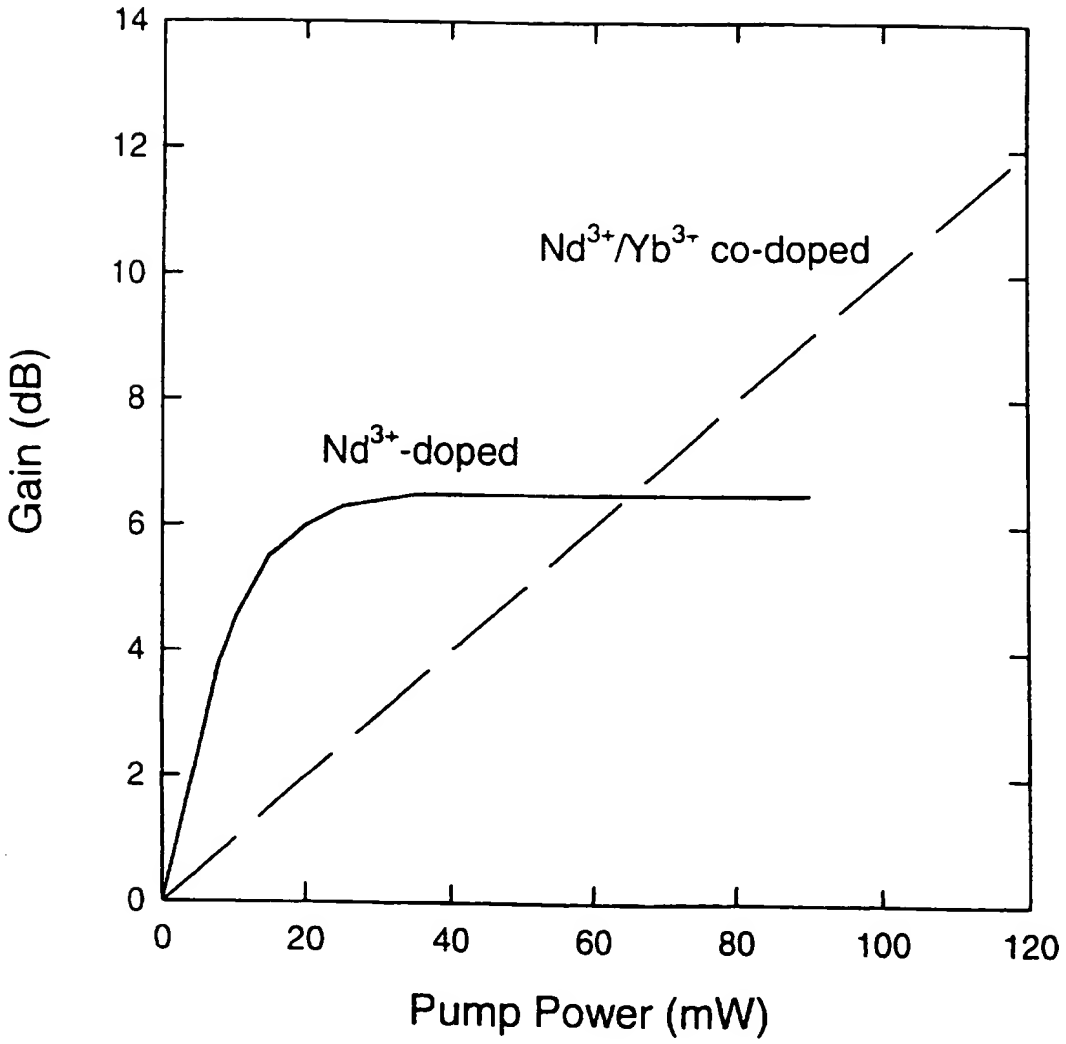

14
12
10
8
6
4
2
0
Gain (dB)
Nd3+/Yb3+ co-doped
Nd3+-doped
0
20
40
60
80
100
120
Pump Power (mW)

FIG. 5.

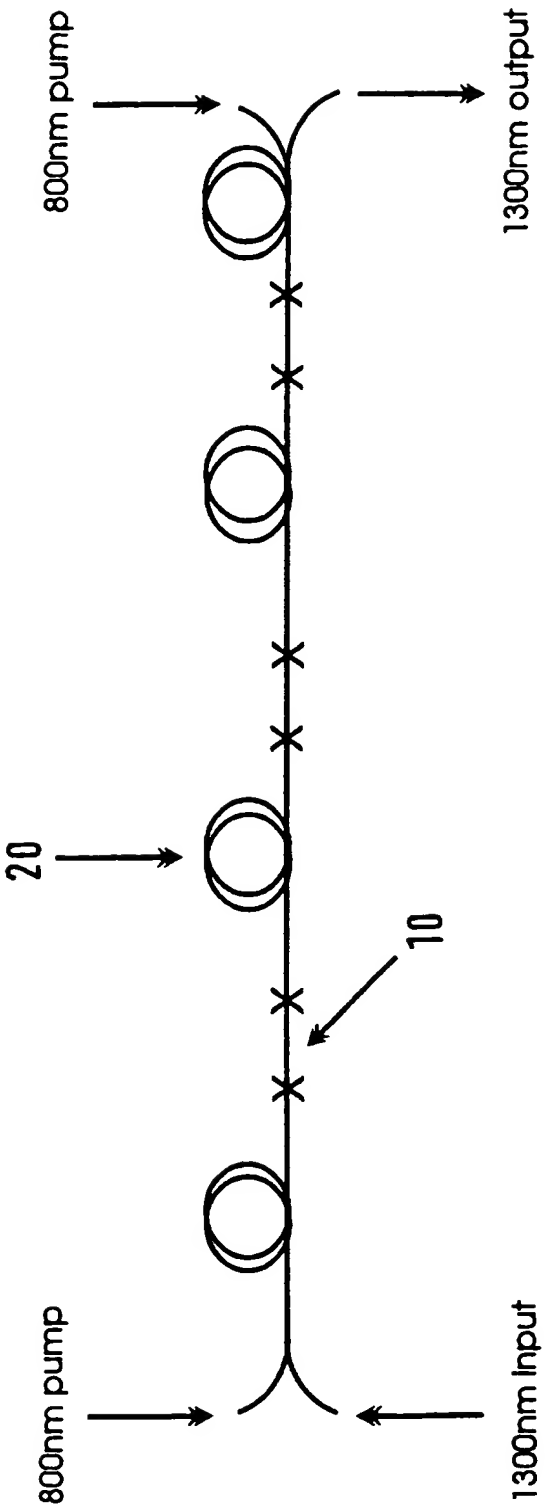


FIG. 6.

FIG. 7.

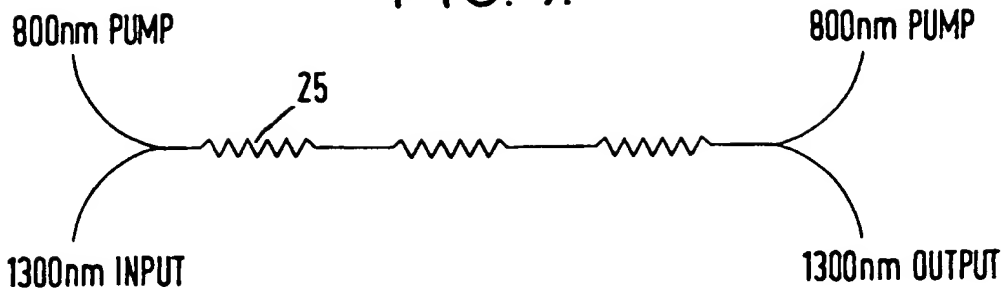
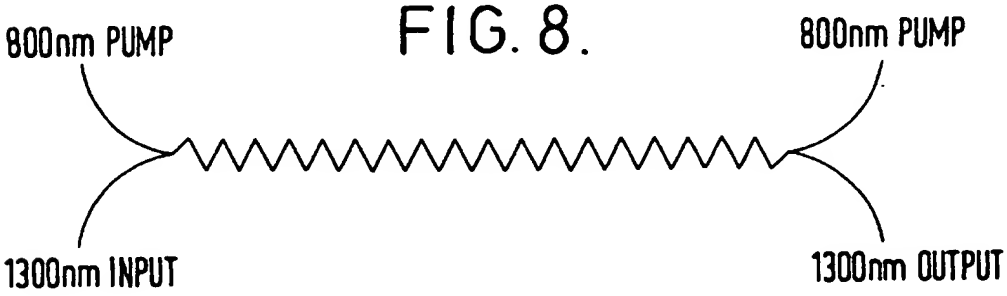


FIG. 8.



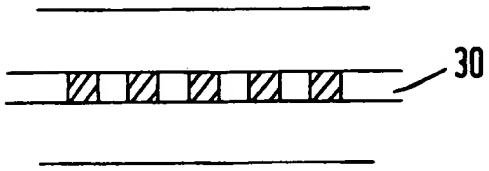


FIG. 9.

FIG. 10.

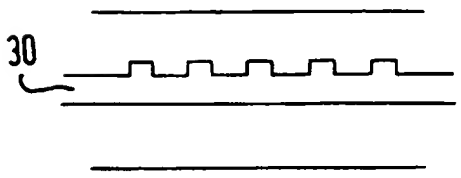
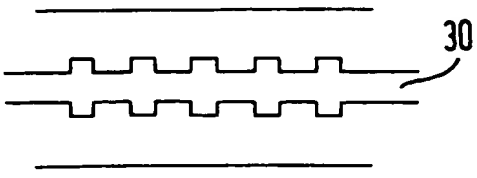


FIG. 11.



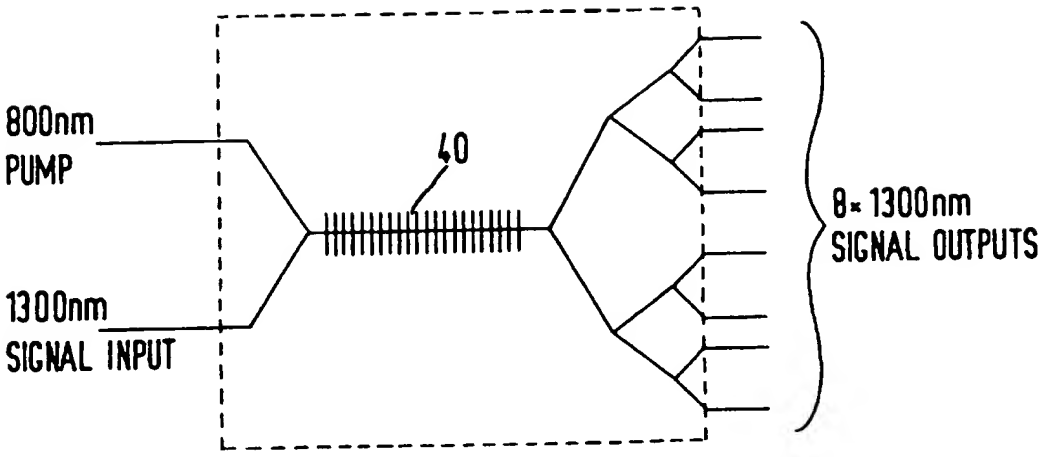

800nm
PUMP
1300nm
SIGNAL INPUT
40
8× 1300nm
SIGNAL OUTPUTS

FIG. 12.

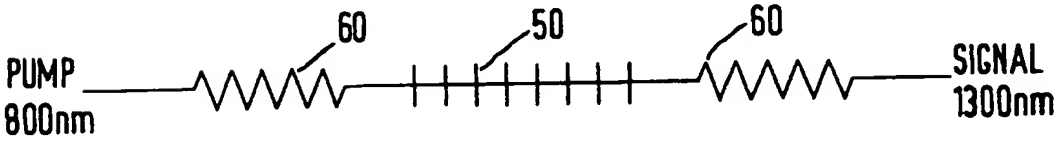

PUMP
800nm
60
50
60
SIGNAL
1300nm

FIG. 13.

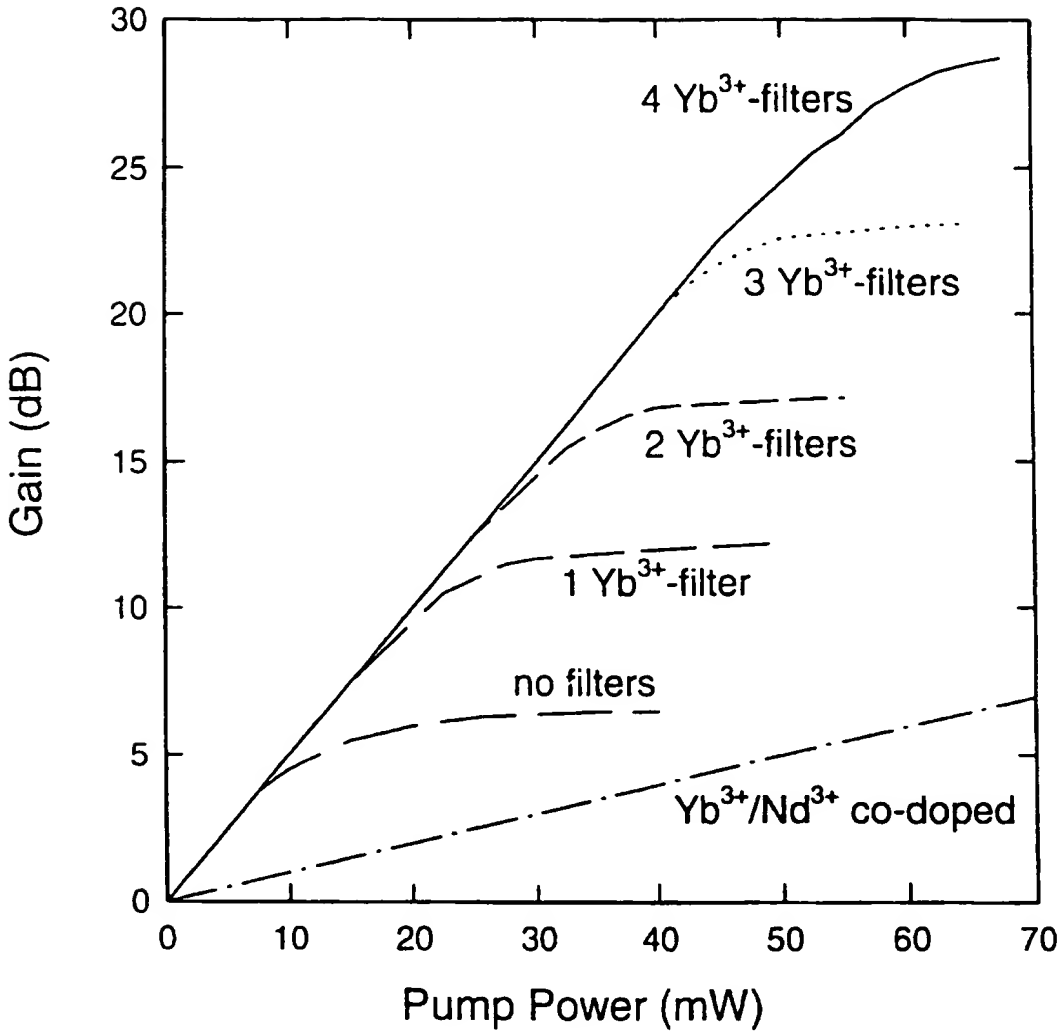

30
25
20
15
10
5
0
Gain (dB)
0
10
20
30
40
50
60
70
Pump Power (mW)
4 Yb3+-filters
3 Yb3+-filters
2 Yb3+-filters
1 Yb3+-filter
no filters
Yb3+/Nd3+ co-doped

FIG. 14.

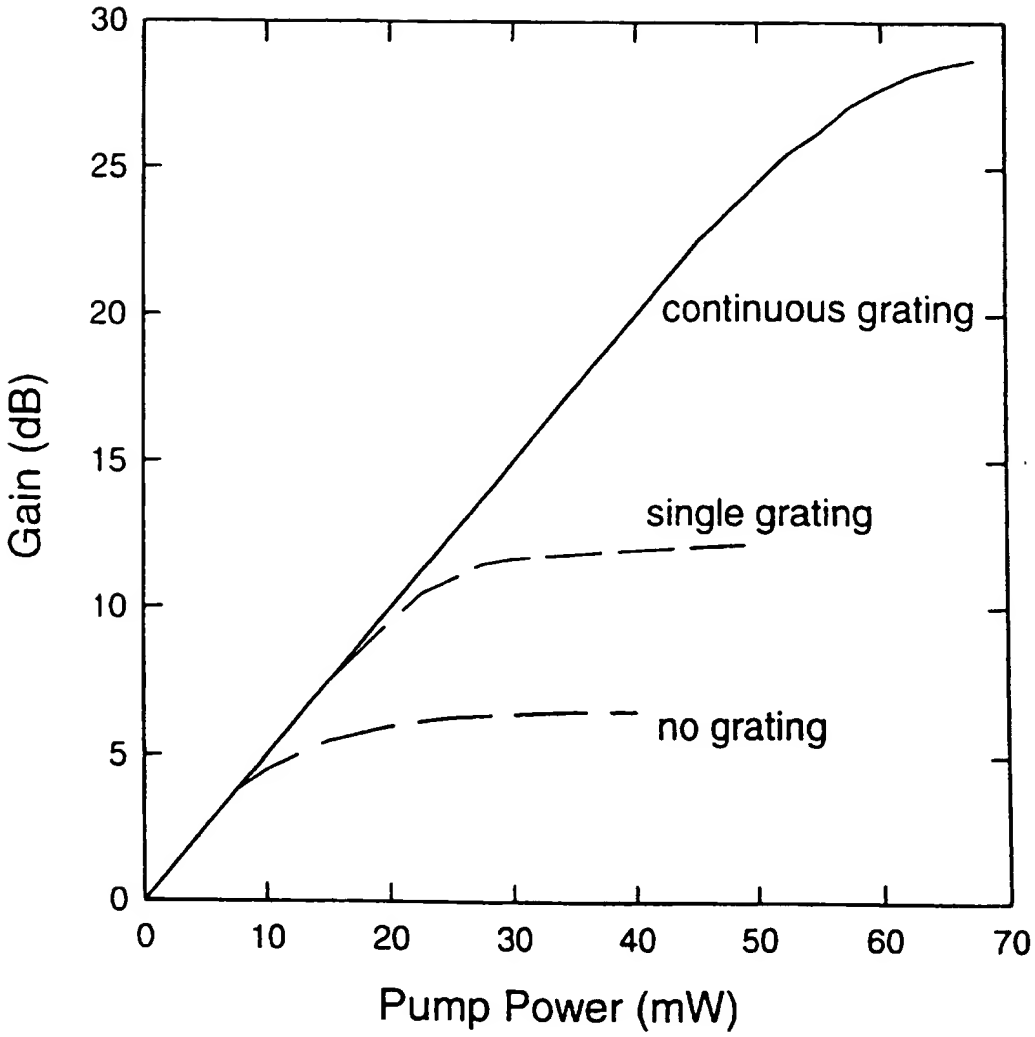

30
25
20
15
10
5
0
Gain (dB)
continuous grating
single grating
no grating
0
10
20
30
40
50
60
70
Pump Power (mW)

FIG. 15.